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SPECTRAL INTEGRATION OF INTERAURAL TIME DIFFERENCES IN AUDITORY LOCALIZATION

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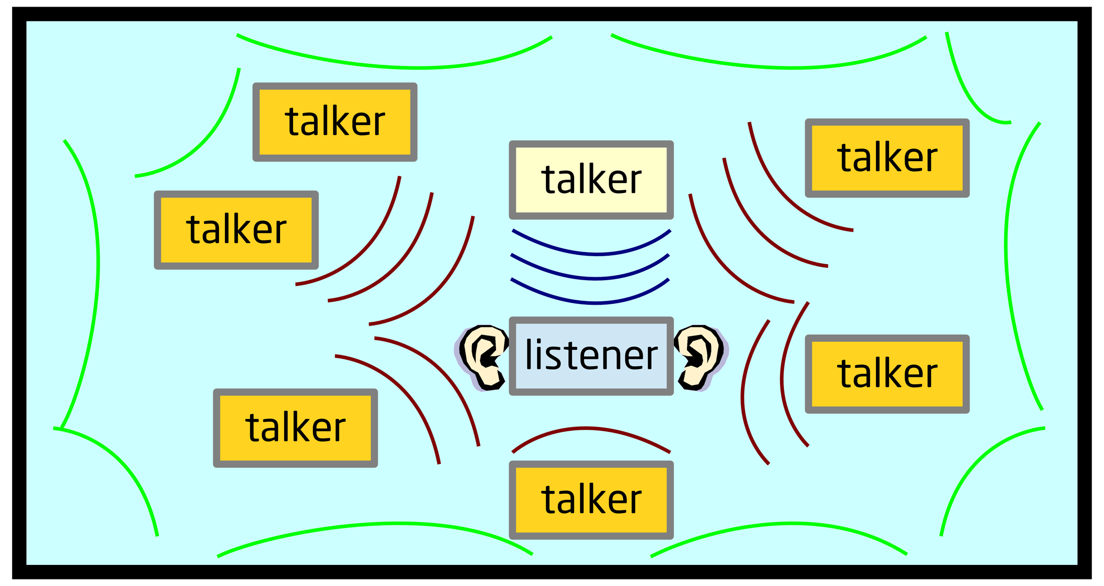
Introduction

The communication skills of normal-hearing persons in complex acoustical environments are remarkable and only partially understood. Such complex scenario typically contains multiple sound sources and room reverberation as shown in the following sketch:



Several studies have shown that the ability to communicate (listen) in realistic environment is supported by localization cues (e.g., Bronkhorst, 2000). Localization in controlled conditions has been extensively described and mostly relies on interaural time differences (ITDs) at low frequencies. However, many aspects of realistic acoustical scenarios can affect the processing of ITD in localization tasks:

- Hard surfaces (walls, ceiling, floor, furniture...) cause reverberation, which leads to a decrease of the interaural correlation (IC) of the signals at the listeners' ears (Kuttruff, 2000).
- Sound sources (main talker or interfering sources) occur at various positions on the horizontal plane (azimuth angle) but the auditory accuracy to discriminate ITDs decreases with increasing azimuth angle (reference ITD) (Hafter, 1975).
- Acoustical information is carried by speech, a broadband signal, and the spectral integration of ITDs might be influenced by room reverberation and sound source azimuth angle.

Models of spectral weighting and integration of ITDs have been proposed in previous studies (e.g., Raatgever, 1980, Stern et al. 1988, Shackleton et al. 1992). However the effect of realistic listening conditions (room reverberation, azimuth angle) on such spectral integration process has not been studied in detail.

Research Question

How ITD-based localization is influenced by realistic acoustical conditions?

This study investigated the influence of room reverberation and azimuth angle on ITD-based localization for broadband signals. A free-pointing localization experiment with broadband signals was conducted, in which the IC and the ITD values were varied. A conceptual model to predict the ITD-based localization in realistic conditions is proposed. The model assumes a spectral decomposition of the signal in the cochlea, independent external and internal noise sources and an optimal spectral integration of information after spectral weighting. The spectral weighting was derived from ITD thresholds that were measured as a function of frequency, IC, and reference ITD, using the concept of signal detection theory.

Experiments

- **ITD Discrimination:** ITD just noticeable difference – discrimination task – 3-interval, 3-alternative forced choice – 2-down 1-up adaptive procedure – 300-ms long signals – narrowband (1 ERB) as a function of center frequency or broadband (100-3000Hz) signals – ongoing ITDs – 4 listeners – 4 repetitions – headphone presentation.
  - ***Experiment A***: ITD in reference intervals: 0µs – Interaural correlation: 1, 0.97, 0.92 or 0.85
  - ***Experiment B***: ITD in reference intervals: 0, 200, 400 or 600µs – Interaural correlation: 1
  - ***Experiment C***: ITD in reference intervals: 0, 200, 400 or 600µs – Interaural correlation: 0.92
- **ITD Localization:** Lateralization estimate – free pointing task of *pointer* signals on *target* signals – broadband signals consisting of every second 1-ERB-wide bands linearly spread between 148 and 1572Hz for a total of 9 bands – 300-ms long signals – pointer signals: fully correlated, carrying a single adjustable ITD identical in all bands – target signals: fully or partially correlated, ITDs as shown by gray symbols in Figs. D and E – 5 listeners – 12 repetitions – headphone presentation.
  - ***Experiment D:*** Interaural correlation: 1
  - ***Experiment F:*** Interaural correlation: 0.92

Localization model

A functional localization model was designed. It assumes auditory filtering, independent auditory internal and external noise sources, spectral weighting and optimal spectral integration. The spectral weighting and the variance of the noise sources were estimated from the measured ITD thresholds.

Measured ITD discrimination thresholds (τ_{JND}) as a function of center frequency (f), interaural correlation (ρ) and reference ITD (τ_{ref})

$$d'=\frac{\tau_{JND}(f,\rho,\tau)}{\sigma(f,\rho,\tau)} \longrightarrow \sigma(f,\tau,\rho)=\frac{\tau_{JND}(f,\tau,\rho)}{d'}$$

analytical approximation of σ

here, d'=1.28

normalized frequency weights

$$a_i=\frac{\frac{1}{\sigma_i^2}}{\sum_{i=1}^{N}\frac{1}{\sigma_i^2}}$$

optimal integration

Predicted ITD localization: $ITD_{pred}=\sum a_i * ITD(f)$

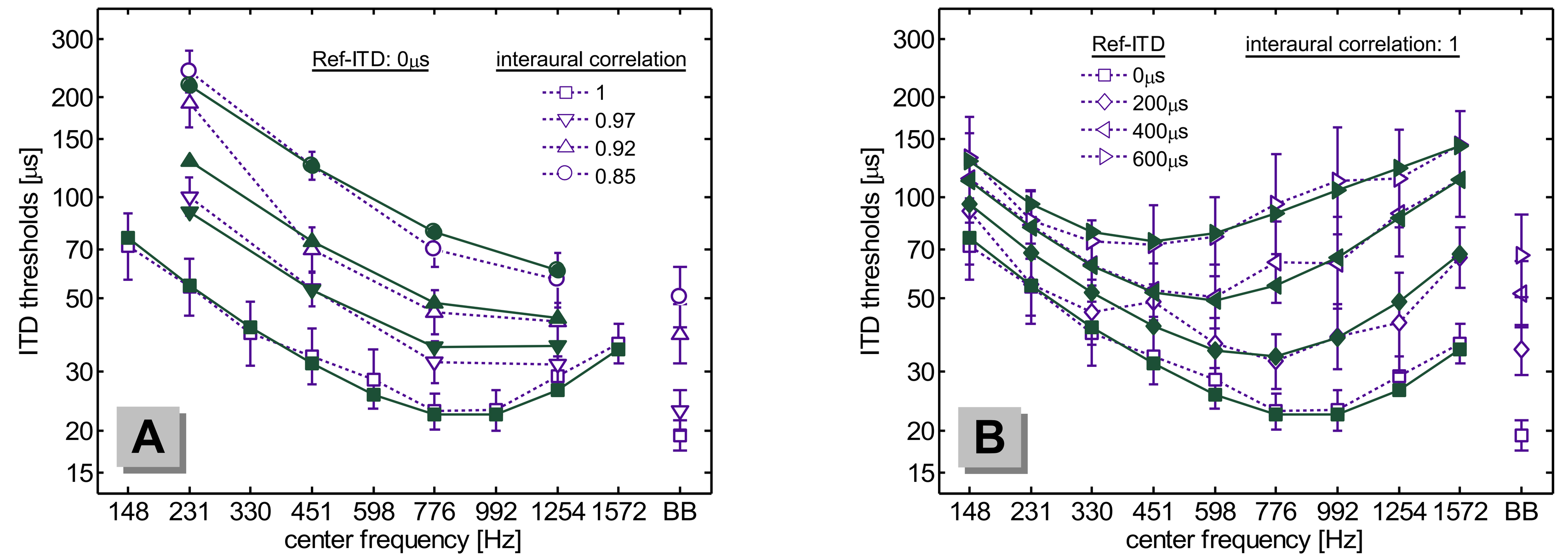
ITD discrimination fitting

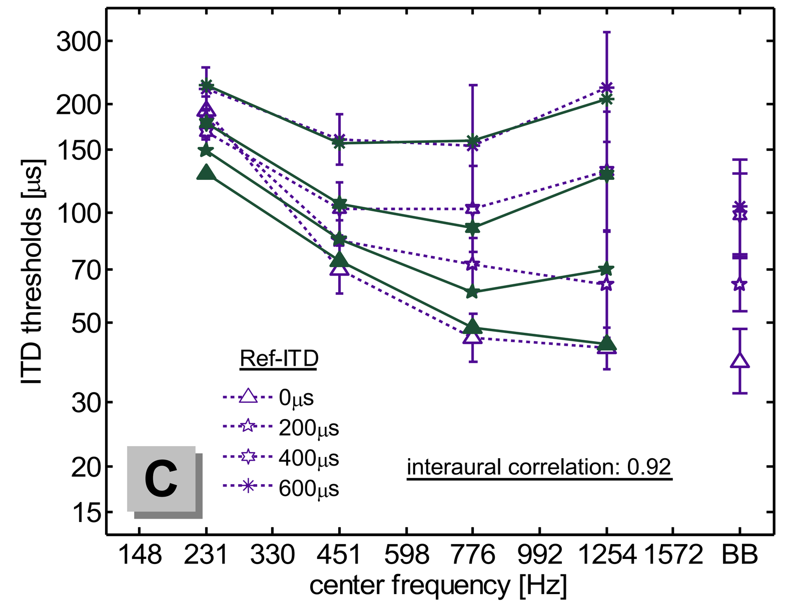
The variance, σ^2 used in the above localization model was derived by fitting analytical functions to the measured ITD data, τ_{JND}, as described above, i.e. assuming $\sigma=\frac{\tau_{JND}}{d}$' and d' = 1.28. The total noise was thereby described by two independent noise sources, i.e.: $\sigma^2=\sigma^2_{internal}+\sigma^2_{external}$

$$\sigma^2_{internal}(f,\tau)=\underbrace{g_{internal}(\tau)}_{\text{overall sensitivity}}.\underbrace{\left(\frac{1}{B_{ERB}(f).f}\right)}_{\text{phase-locking}}.\underbrace{\left(1+\frac{f}{f_{internal}(\tau)}^{N(\tau)}\right)}_{\text{loss of fine-structure}}$$

$$\sigma^2_{external}(f,\tau,\rho)=g_{external}(\tau,\rho).\left(\frac{1}{B_{ERB}(f).f}\right).\left(1+\frac{f}{f_{external}(\tau,\rho)}^{N(\tau)}\right)$$

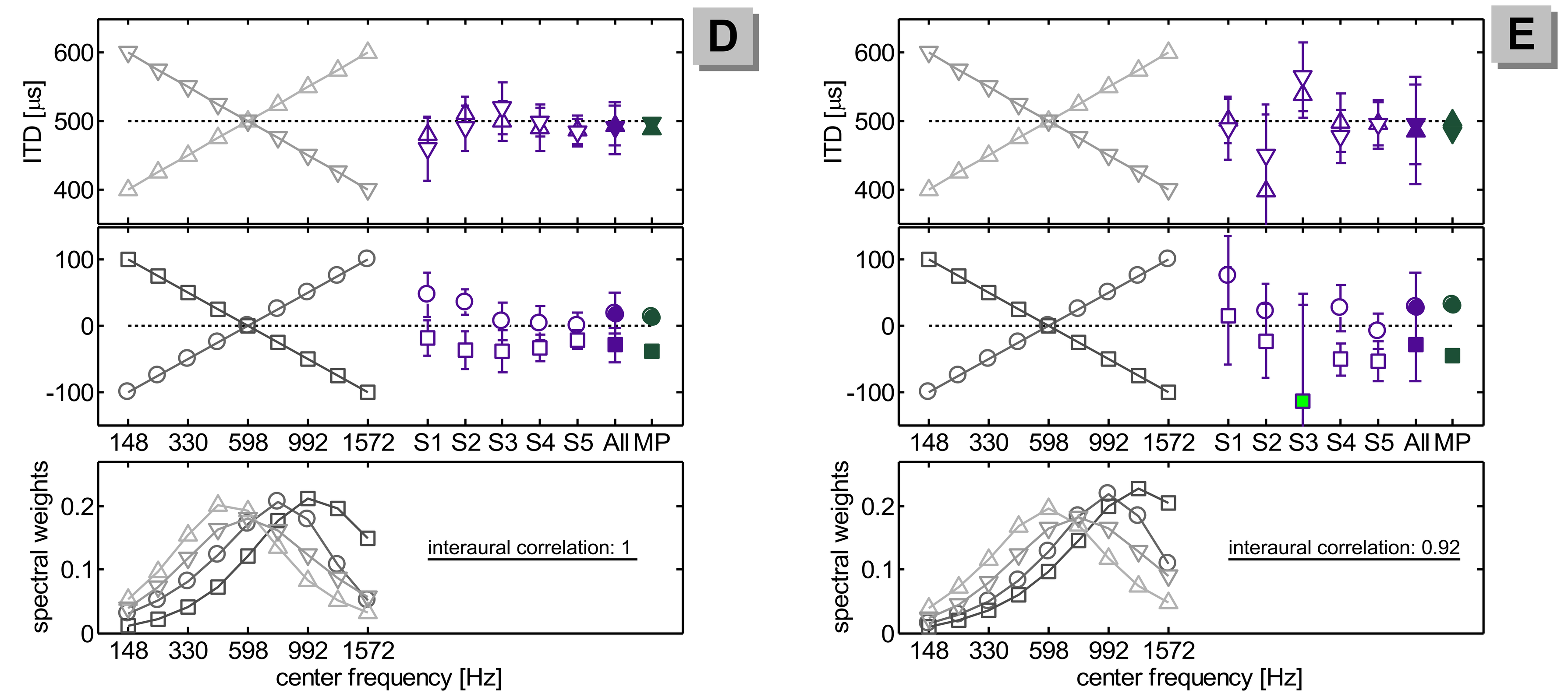
Measured & fitted data - Discrimination





- **Figs. A, B and C** show ITD discrimination thresholds (open symbols) and model fit (continuous line) as a function of frequency for narrow-band (1 ERB) and broadband noise (BB, 100-3000 Hz).
- The model fitting accounts well for the data and provides an estimate of the variance of the internal and external noises limiting the ITD discrimination process.

Data & predictions - Lateralization



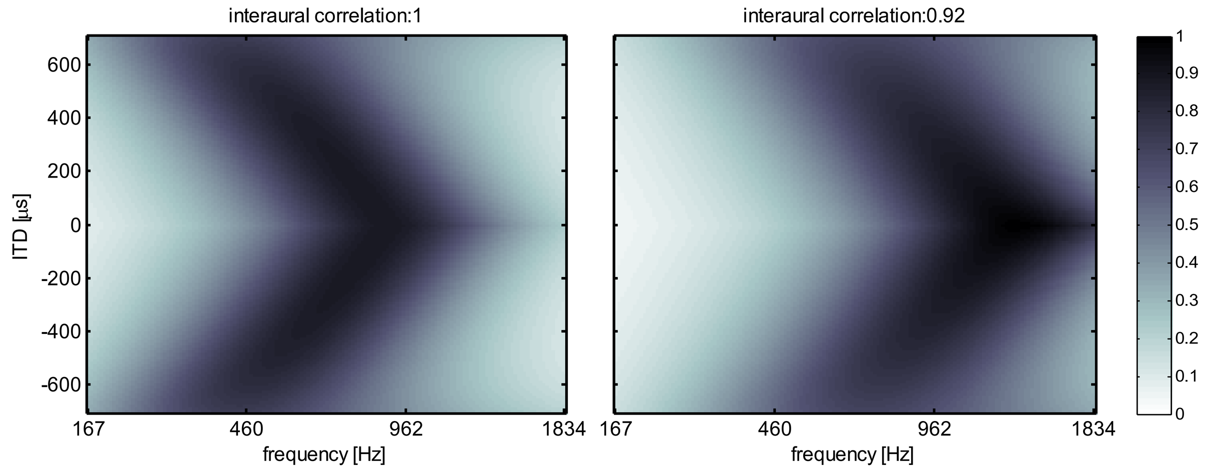
Figs. D and E show the result of the localization experiment for IC of 1 and 0.92. The two upper panels show the ITD in each frequency band of the stimuli (connected gray symbols), the individual localization results for subjects S1-S5 (open blue symbols), the average performance (All, filled blue symbols) and the model predictions (MP, filled red symbols). The bottom panels show the spectral weights derived from the ITD discrimination data. Each curve corresponds to the weighting applied to the ITD values of the localization stimuli, shown here with corresponding symbols and gray shades.

Discussion

ITD discrimination:

- For IC=1 and reference ITD = 0µs, the dependence of the ITD thresholds as a function of frequency is accounted for by a phase-locking mechanism for frequencies below 900 Hz and a fine-structure loss for frequencies above 900Hz.
- Both a decrease in IC or an increase in reference ITD lead to an increase in ITD thresholds.
- The lowest of ITD thresholds obtained with narrowband signals shifts towards lower center frequencies for low IC and large reference ITD, suggesting a change in spectral weighting as a function of IC and reference ITD.

Derived spectral weights:



Normalized frequency weights as a function of frequency and ITD for two IC values. Weights were derived from the ITD discrimination data. Dark colors represent large weights.

- Dominance of a limited spectral range for all combinations of IC and ITD.
- The dominance region is around 900Hz for IC = 1 and ITD = 0 and is shifted towards lower frequencies for larger ITD values.
- The dominance region is also shifted towards higher frequencies for lower IC values.

ITD Localization:

- The data are well accounted for by the proposed localization model. Both a reduction in IC and the position of the sound source have an effect on the spectral weighting and thus on the perceived location.
- The localization of ITD is well predicted as a function of ITD and IC.

Conclusion

- Localization model accounts for a number of factors that affect ITD-based localization in realistic acoustic scenarios.
- Spectral integration in ITD-based localization can be accounted for assuming optimal information integration and a spectral weighting that depends on interaural correlation and the ITD of the signals.

Outlook

- Single-channel or multi-channel processing?
- Test localization where ITD and IC are varied within one stimulus

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